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A novel thermoacoustic system for natural gas liquefaction

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Abstract

A novel thermoacoustic system for natural gas liquefaction is introduced in this paper. It is a ring structure composed of four thermoacoustic heat engine units. Each thermoacoustic heat engine unit is connected to a thermoacoustic refrigeration unit in parallel. There is no moving part in the whole system. The working fluid is environmentally friendly helium gas. In addition, the system can be used to liquefy natural gas by consuming small partial natural gas. The 4-stage acoustically resonant system is simulated, and its thermal performance is analyzed. The mean pressure in the system is 8MPa. The heating temperature is 923K, and the ambient temperature is 303K. According to the preliminary simulation, the cooling power at 130K of the system is about 100kW, with the exergy efficiency about 30%. The thermal performance of the system will improve after optimization. The novel acoustically resonant system shows broad application prospects in the field of natural gas liquefaction.

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Keywords: Acoustically resonant; Thermoacoustic; Heat engine; Refrigeration; Liquefied natural gas;

1. Introduction

Thermoacoustic heat engines can be used to drive thermoacoustic refrigerators to form thermoacoustically driven refrigerators (TDRs). The TDR has no moving parts in the whole system, with projected low cost, high reliability, long life and low maintenance. In 1989, Radebaugh and Swift (from Los Alamos National Laboratory) constructed the first TDR which gives a no-load cooling temperature about 90K [1]. It is an orifice pulse tube refrigerator driven by a standing wave thermoacoustic heat engine. In 1997, Chart, with major technical support from Los Alamos National Laboratory, built and successfully operated the first TDR for natural gas liquefaction. It achieved a liquefaction capacity of 140 gallons per day, producing 2kW of cooling power at -140^{o} C. It can liquefy about 40% of the gas stream while burning 60% [2, 3]. In 1999, Backhaus and Swift developed a traveling wave thermoacoustic heat

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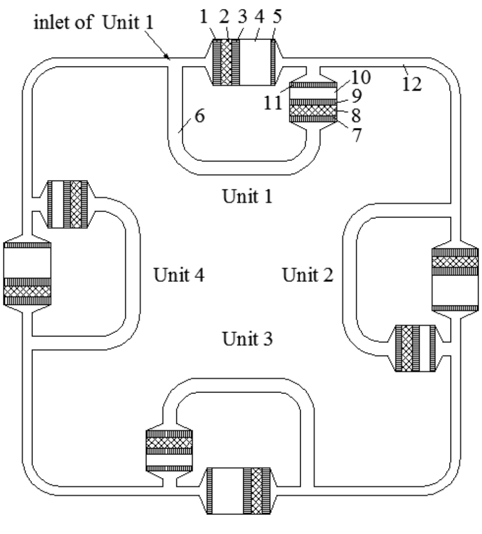
engine with an efficiency of 41% of Carnot [4, 5]. Begin mid 1999, a traveling wave thermoacoustic heat engine driven orifice pulse tube system was developed to achieve a liquefaction capacity of 500 gallons per day. In the system, three refrigerator are used, driven in parallel by thermoacoustic wave. The design calls for the engine and resonator to deliver 30kW of acoustic power to the refrigerators, whose combined cooling power is 7kW [2, 3]. In recent decades, some other TDRs were developed. However, the cooling power of all the previous TDRs is less than 10kW. It is difficult to meet the need for natural gas liquefaction in practice. In this paper, a novel thermoacoustic system is proposed for natural gas liquefaction. The numerical simulation results show that the cooling power at 130K of the system is about 100kW, with the exergy efficiency more than 30%.

2. The thermoacoustic system

Figure 1 shows the schematic of the new thermoacoustically driven refrigerator. It's a 4-stage acoustically resonant system. It is a ring structure composed of four identical thermoacoustic heat engine units and four identical thermoacoustic refrigerator units. Each thermoacoustic heat engine unit consists of a main water-cooled heat exchanger (EMHX), regenerator (ER), heater, thermal buffer tube (ETBT), and secondary water-cooled heat exchanger (ESHX). Each thermoacoustic refrigerator unit consists of a phase shift tube (PST), main water-cooled heat exchanger (RMHX), regenerator (RR), cold end heat exchanger (CHX), thermal buffer tube (RTBT), and secondary water-cooled heat exchanger (RSHX). Each thermoacoustic heat engine unit is connected to a thermoacoustic refrigeration unit in parallel. Between every two parallel units is a resonator tube. The main dimension of each component is listed in Tables 1 and 2. The length of each cone connecting tube in the system is 50mm.The ER and RR is packed with stainless steel screens. The wire diameter of the stainless steel screens in the ER is 0.052mm, with porosity of 0.8. The wire diameter of the stainless steel screens in the RR is 0.03mm, with porosity of 0.81. The diameter of each resonant tube is 60mm, with length of 1800mm.



1-EMHX; 2-ER; 3-Heater; 4-ETBT; 5-ESHX;
6-PST; 7-RMHX; 8-RR; 9-CHX; 10-RTBT; 11-RSHX; 12-Resonant tube

Fig. 1. Schematic of the 4-stage acoustically resonant thermoacoustic refrigerator

Table 1. Dimensions of the thermoacoustic heat engine unit

	Diameter/mm	Length/mm
EMHX	300	50
ER	300	70
Heater	300	50
ETBT	300	200
ESHX	300	30

Table 2. Dimensions of the thermoacoustic refrigerator unit

	Diameter/mm	Length/mm
PST	90	1500
RMHX	300	40
RR	300	70
RCHX	300	40
RTBT	300	75
RSHX	300	30

3. Numerical simulation method

The computation is performed by using the DeltaEC6.2 software [6]. Based on the classical thermoacoustic theory, DeltaEC is the computation software of thermoacoustic equipment, which includes modules for heat exchangers, regenerators, ducts, acoustic compliance, pistons etc. The thermoacoustic system can be simplified as some modules to simulate. The simulation is carried out under constant heating temperature of 923K (650 $^\circ C$) and ambient temperature of 303K (30 $^\circ C$). The working gas of the system is helium, with mean pressure of 8MPa.

4. Performance prediction

The prediction performance of the thermoacoustic system is given in this section. Since the construction of the system is symmetric, the performance of each unit is identical. For simplicity, the results showing in the following picture just include one unit.

With the cooling temperature of 130K, the phase angel of oscillating pressure (p) leading volume rate (U), and time-averaged acoustic power flux in the system are given in the following figures. Figures 2(a) shows the profiles in the thermoacoustic heat engine unit and the connecting resonant tube, i.e. from the inlet of Unit 1 to the inlet of Unit 2. Figures 2(b) shows the profiles in the thermoacoustic refrigerator unit.

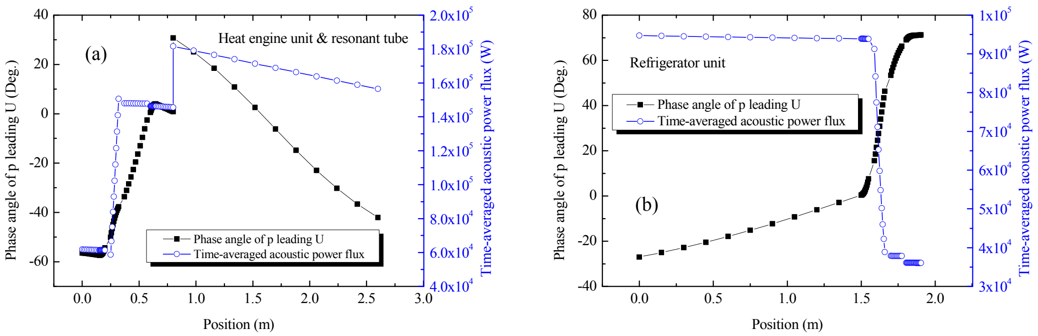


Fig.2. Phase angel of p leading U and Time-averaged acoustic power flux

As seen in figure 2, the phase difference between oscillating pressure and volume rate in the ER is from $15.6° \sim 46.3°$. The resonant tube consumes acoustic power of 25.1kW.The PST just consumes a few acoustic power. It adjusts the acoustic field to make the thermoacoustic refrigerator works efficiently. The phase difference between oscillating pressure and volume rate in the regenerator is from $-50.1° \sim -37.7°$. The thermoacoustic refrigerator consumes acoustic power of 58.66kW and produces cooling power of 25.18kW.

Figure 3 shows the cooling power and thermal exergy efficiency ($\eta_{ex} = Q_c \cdot (T_0 / T_c - 1) / [Q_h \cdot (1 - T_0 / T_h)]$) with respect to cooling temperature. The cooling power of each unit at 130K is 25.18kW. The thermal exergy efficiency of the system is 30.2%. That means the cooling power at 130K of the whole system is 100.72kW, with thermal exergy efficiency of 30.2%. Under this operating condition, the COP is 0.153. The frequency of the system is 40.96Hz.

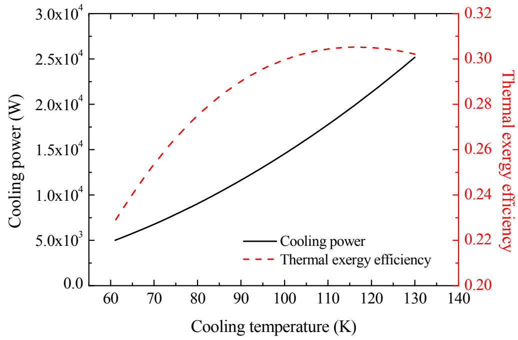


Fig. 3. Cooling power and thermal exergy efficiency vs. cooling power

5. Conclusions

A novel thermoacoustic system, 4-stage acoustically resonant thermoacoustic refrigerator, is proposed in this paper. According to the simulation, the cooling power at 130K of the whole system is about 100kW, with the exergy efficiency about 30%. It can be used in the field of natural gas liquefaction.

Acknowledgements

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References

[1] Radebaugh R, McDermott KM, Swift GW and Martin RA. Development of a thermoacoustically driven orifice pulse tube refrigerator. *Proceedings of 6th Interagency Meeting on Cryocoolers* 1989; 205-220.

[2] Wollan, JJ, Swift GW, Backhaus SN, and Gardner DL. Development of a thermoacoustic natural gas liquefier. *No. LA-UR-02-1623. Los Alamos National Laboratory* 2002.

[3] Swift GW, and Wollan JJ. Thermoacoustics for liquefaction of natural gas. *LNG Technology* 2002; 21-26.

[4] Backhaus S, and Swift GW. A thermoacoustic Stirling heat engine. *Nature* 1999; 399: 335-338.

[5] Backhaus S, and Swift GW. A thermoacoustic-Stirling heat engine: Detailed study. *The Journal of the Acoustical Society of America* 2000; 107: 3148-3166.

[6] Ward Bill, Clark John and Swift Greg. Design Environment for Low-Amplitude ThermoAcoustic Energy Conversion, DELTAEC Version6.2 Users Guide; 2008.

Biography

Limin Zhang：
I received PH.D in Refrigeration and Cryogenic Engineering from Graduate University of Chinese Academy of Sciences in 2013. My research focuses on thermoacoustic heat engines and high power pulse tube cryocoolers. My most recent effort has been experimental and numerical analysis of acoustically double-acting thermoacoustic systems.